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THE SIGNIFICANCE OF THE JUPITER SWINGBY
MODE FOR INTERPLANETARY MISSIONS

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ABSTRACT: The astrodynamic theory of gravity-assisted interplanetary spacecraft trajectories is discussed, followed by an analytical study of Saturn, Uranus, Neptune, and Pluto missions with gravity assists from Jupiter. Time factors, launch opportunities, and reduced propulsion requirement due to the utilization of the gravity field are covered. Transfer trajectories utilizing several gravity fields for a multiple interplanetary mission are considered as well as solar missions and missions to comets. Problems connected with scientific purpose, trajectory accuracy, and mission duration are briefly pointed out.

SYNOPSIS

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The majority of future interplanetary missions, such as exploration of the neighborhood of the sun and of the outer solar system, will require unusual propulsion energies for the ballistic transfer trajectories. By precisely calculated perturbation of these trajectories in the gravity field of suitable planets, however, it is possible to reduce the propulsion requirements for launch from Earth and in special cases the flying time as well (swingby mode).

In this report, it is attempted to extract a conspectus of the significance of the Jupiter swingby mode for interplanetary missions from the numerous publications in this field.

SYMBOLS AND NOMENCLATURE

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r	[AU]	Radius vector
V	[km/sec]	Velocity relative to the Sun
ΔV	[km/sec]	Magnitude of the vectorial velocity increment
ΔE	[km ² /sec ²]	Energy increment

* Numbers in the margin indicate pagination in the foreign text.

v	[EMOS]	Hyperbolic excess velocity relative to mean orbital speed of Earth
K	[km ³ /sec ²]	Gravity constant
e	[-]	Numerical eccentricity
i	[°]	Inclination to the ecliptic

INDICES

min	Smallest distance
P	Planet, pericenter
A	Apocenter
+	Trajectorial elements after Jupiter swingby

1. INTRODUCTION

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Astronomy is acquainted with several instances in which the orbits of comets have been modified considerably by the gravity fields of large planets. A case in point is Comet 1889 V, which in 1886 passed the planet Jupiter at a small distance and whose orbit was disturbed by the gravity force of Jupiter, according to theoretical computations. This additional mass force can have either an accelerating effect, in which case the affected body is carried into the outer solar system, or it can decelerate the body, in which case it passes into the inner solar system. Comet research provides an example: Comet 1886 III was hurled out of our solar system by a close passage of Jupiter.

Because of those circumstances, it seemed natural to investigate the extent to which this kind of orbit perturbation could be utilized for astronautics, and which planet would be the most suitable for the purpose. Apart from the coincidental findings of comet physics, these studies have been purely theoretical in kind. Now, however, results of such an experiment that was carried out intentionally are available.

The Mariner Venus probe launched on 14 June was intended to pass Venus after about 3.5 months flying time at a distance of 3200 km (about 1.5 Venus radii). The transfer trajectory and encounter were planned such that the probe would undergo a change of course due to the gravity field of Venus to bring the probe closer to the sun than would have been possible without the Venus flyby.

As we know, without a Venus passage the probe would have reached a perihelion of about 0.72 AU. As a result of the flyby occurring on 19 October at a distance of 3968 km, the probe will now approach the sun to within 0.58 AU. Hence, this mission can be regarded as a first successful utilization of the swingby mode.

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The swingby mode is taken generally to mean the intentional utilization of the gravity of celestial bodies (planets, moons) to alter the trajectory of passing man-made spacecraft. Other names to be found in the American literature for this technique are "gravity-turn," "gravity assist," "gravity deflection," etc.

2. PHYSICAL EXPLANATION OF THE PROCESS

The exact explanation of interplanetary free-flight trajectories of space probes requires the solution of a many-body problem. The number of bodies to be included depends upon the type of mission. For example, at least the masses of Earth, Sun, Jupiter, and probe would have to be included for a direct mission to Jupiter.

The planning and systematic selection of transfer trajectories for a certain mission, however, is facilitated by the closed solutions of the two-body problem, which, moreover, supply good starting values for exact computations.

A Jupiter transfer trajectory would be segmented into the regions probe-Earth, probe-sun, and Jupiter-probe. Thus, three symmetric gravity potentials are examined in succession. Within the individual regions (spheres of influence), the gravity force of the relevant central body is substantially greater than that of the others. Therefore, the individual segments of the trajectories are conic sections. The heliocentric phase is generally an ellipse. The planetocentric phases must be hyperbolas, since escape parabolas merely lead out of the sphere of influence of the planets, but from a heliocentric standpoint have the same orbital energy as the corresponding planetary orbit itself. The heliocentric orbit is obtained from the radius vector of the probes at the periphery of the sphere of influence in the heliocentric system and by vector addition of the planetocentric velocity of the probe and heliocentric velocity of the planet. In actual practice, the relationships in the sphere of the target planet are merely an inversion of the launch relationships. /6

The trajectory around the target planet is illustrated by Figures 1 and 2. The points labeled E represent the entry of the probe into the sphere of influence. At point A (exit), the influence of the sun is greater than that of Jupiter. Two cases have been examined (Figs. 1 and 2). In the first case, the value of the heliocentric probe velocity upon exit from the sphere of influence is greater than upon entry. Hence, the probe was accelerated by the gravity of Jupiter. In Case 2, the probe is decelerated from the heliocentric standpoint. The determination of the jovicentric probe velocity upon entry and exit can be drawn from the velocity triangles. It can be seen by inspection whether an acceleration is produced by the flyby if the velocity on the outgoing asymptote is broken down into two components parallel and perpendicular, respectively, to the velocity of the planet. If the parallel component points in the direction of the velocity of the planet, the probe is accelerated; if it points in the opposite direction, the probe is decelerated. /7

In the former case, the kinetic energy of the probe increases from the heliocentric standpoint; in the latter case, it decreases. Since in the sun-Jupiter-probe system the total energy contained

within the Keplerian orbit of Jupiter and of the probe must remain constant, at the same time the energy value of Jupiter will vary as a result of the variation of the energy of the probe. If the radius of influence of Jupiter is neglected as compared with the average sun-Jupiter distance, the variation of the potential energy contribution of the probe can be disregarded. Thus, if the probe is accelerated, the heliocentric velocity of Jupiter must be decelerated and vice versa. As can be estimated on the basis of the principle of the conservation of energy, however, the variation of the velocity of Jupiter is negligible owing to the large mass of the planet as compared with that of the probe.

For greater clarity, Figures 1 and 2 show only the relationship for a two-dimensional flyby and, hence, would be valid only for the ideal solar system of coplanar planetary orbits. In actual practice, the inclination of the trajectorial plane to the ecliptic will be altered by swingby maneuvers.

The analytic treatment of trajectory change by swingby maneuvers will not be repeated here, since it has been carried out in a great many publications. The reader can obtain relevant information in References [1], [5], and [6]. As reported there, and as can be seen from Figure 1, the vector of the probe velocity after the flyby is a function of the following quantities:

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Magnitude and direction of the velocity vector of the probe entering the sphere of influence with respect to the direction of the velocity of the planet.

The point of entry of the probe into the sphere of influence, referred to a coordinate system centered on the disturbing planet.

The mass and, hence, the gravity constant of the planet.

Among all the major parameters, the gravity potential of the planet is the most important.

A useful measure for assessing whether a planet is particularly suitable for swingby maneuvers is found to be the maximum energy increment ΔE_{\max} of interplanetary transfer trajectories and the maximum velocity increment ΔV_{\max} due to the flyby.

According to Niehoff [1], the two criteria for all planets of our solar system are found to have the maximum values which are compiled in Table 1. The values were computed with the relations derived in Reference [1]. ΔV is the magnitude of the vector difference between the heliocentric probe velocity upon entry into the sphere of influence of the planet and that upon exit from the sphere of influence. ΔE is the difference in kinetic probe energy between these two states. In magnitude, ΔV_{\max} is equal to the central orbital velocity of a satellite around the planet at the distance of the vertex of the flyby hyperbola.

As can be seen from the table, the list of bodies is headed by the planet Jupiter, with a maximum energy increment of 583.7 km^2/sec^2 and a maximum velocity increment of 42.6 km/sec . The latter value becomes more graphic if it is borne in mind that the perihelion velocity of a heliocentric escape parabola starting at 1 AU is equal to about 42.1 km/sec . The computed maximum values are referred to 1 planet radius as the pericenter distance. Although the planet radii include the atmosphere if present, for safety reasons (aerodynamic drag) it will of course not be possible to fly by the planet at such close range, and, hence, the maximum values of ΔE and ΔV will not be attained. The table also indicates that the transfer trajectories to the four large outer planets that provide the maximum increment of velocity and energy are escape hyperbolas from our solar system even before the encounter with these planets. The trajectory to Jupiter has a perihelion between the orbits of Mercury and Venus. The perihelion of the trajectory to Uranus is even as close as only 0.03 AU from the sun.

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An important relation is that of the maximum energy and velocity increments to the incoming hyperbolic excess velocity of the probe upon entry into the sphere of influence. As can readily be demonstrated, the necessary hyperbolic excess velocity for the maximum energy increment is exactly ΔV_{max} [1].

In the following Figures 3 and 4, the energy and velocity increments were plotted as a function of the hyperbolic entry velocity. The comparison of Figure 3 with Figure 4 (see also Table 1) shows that when the values are arranged in increasing magnitudes for the nine planets the maximum energy increments have a different sequence than do the maximum velocity increments. For example, with respect to ΔE_{max} , Venus and Earth are in third and fourth place. In the sequence of ΔV_{max} , conversely, the four large outer planets, Jupiter, Saturn, Neptune, and Uranus, are in the first places.

This result, however, is easy to explain if the above-mentioned relations for ΔE_{max} and ΔV_{max} and the velocities of the planets in Table 1 are borne in mind. Although Venus, for example, supplies a velocity increment of only 7.2 km/sec , owing to its high orbital speed of 35.1 km/sec , as compared with that of Neptune, it can effect a substantially greater energy increment.

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Figure 4 shows the relation between the hyperbolic excess velocity of the probe* upon entry into the sphere of influence and the magnitude of the change of the heliocentric probe velocity by the gravity field of the pertinent planet, on the assumption that the minimum distance of the pericenter is 1 planet radius. A swingby in the gravity field of a planet requires a minimum excess velocity

* TRANSLATOR'S NOTE: Misprint in original text.

that is found from the Hohmann transfer to the respective planet for the ideal solar system. These excess velocities mark practically the beginning of the curves plotted in Figures 3 and 4.

In Table 1, the magnitudes of the increments of energy and velocity as a result of Hohmann encounter are listed together with the pertinent transfer times, which provide a better synopsis.

Figure 4 also indicates that for interplanetary missions from the Earth two planets are suitable for intentional calculated swingby of probe trajectories, which are Venus for missions to the inner solar system and Jupiter for missions into the outer solar system. Whereas a maximum velocity increment of only 7.2 km/sec is possible with Venus, a Hohmann transfer to Jupiter supplies an increase or decrease of probe velocity of 10.5 km/sec.

TABLE 1. MAXIMUM INCREMENT OF VELOCITY AND ENERGY IN THE GRAVITY FIELD OF EACH PLANET (COMPILED ON THE BASIS OF [1] AND [5])

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Planet	Mass Earth = 1	Orbital Speed [km/sec]	Maximum Energy Increment [km ² /sec ²]	Maximum Speed Increment [km/sec]	Peri- helion Before Swingby [AU]	Aphelion Before Swingby [AU]	Peri- helion After [AU]	Aphelion After [AU]	Hohmann Transfer ΔV [km/sec]	Transfer T [d]
1. Jupiter	318.4	13.1	583.7	42.6	0.59	Hyperb.	3.30	Hyperb.	10.8	997
2. Saturn	95.22	9.7	261.7	25.7	0.31	Hyperb.	6.22	Hyperb.	10.4	2209
3. Venus	0.815	35.1	255.2	7.2	0.47	0.77	0.68	1.25	4.8	146
4. Earth	1	29.8	239.4	7.9	0.58	1.09	0.92	2.12		
5. Mercury	0.053	47.9	173.7	3.0	0.31	0.42	0.31	0.53	1.63	106
6. Uranus	14.55	6.8	107.6	15.1	0.03	Hyperb.	13.00	Hyperb.	9.9	5853
7. Mars	0.167	24.1	95.5	3.6	1.16	1.51	1.34	2.40	3.4	259
8. Neptune	17.23	5.4	91.9	16.8	3.26	Hyperb.	19.86	Hyperb.	7.6	11174
9. Pluto	0.900	4.7	42.1	6.9	3.66	100.09	23.85	Hyperb.	5.9	16650
$\Delta E_{\max} = V_p \cdot \Delta V_{\max}$					$\Delta V_{\max} = (Kp/r_{\min})^{\frac{1}{2}}$					

Moreover, the maximum exploitation of the Venus gravity potential calls for a propulsion requirement from Earth of about 0.33 EMOS (e.g., launch in July 1970; transfer time, 95 days). Therefore, the possibilities for utilization of the venerocentric gravity force are restricted to "relatively" modest interplanetary missions. More detailed information on Venus swingby missions can be obtained, for example, from References [12] and [13].

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As already mentioned, the curve of ΔV_{\max} assumes a pericenter distance of 1 planet radius. The response of ΔV_{\max} and ΔE_{\max} to

Jupiter rendezvous with varying pericenter distance of the swingby hyperbolas is shown in Figure 5, which is based on Reference [1]. The curve shows a very marked falloff with increasing pericenter distance. For example, if the minimum distance that can be maintained is only 1.5 Jupiter radii, ΔV_{\max} will decrease to about 19 km/sec, which would be a loss of over 50%.

The outstanding part in the utilization of the swingby mode for complicated interplanetary missions in the coming decade and the more remote future will be played by the planet Jupiter.

Figure 4 does not indicate the propulsion energy that will be needed for launch from Earth nor the associated flying times of the transfer trajectories to Jupiter. In order to obtain a rough synopsis of those quantities, the geocentric and jovicentric excess velocities for transfer trajectories of 340, 440, and 600 days in the years 1975-1980 were plotted in Figure 6 on the basis of Reference [11]. The magnitudes of the velocity increment were also plotted on the basis of Figure 4. Hyperbolic excess velocities appear in the dimensionless form EMOS referred to the mean orbital speed of Earth, 29.8 km/sec. The diagram can be explained in greater detail by reference to an example. If in the year 1978 the planning is limited to a launch window from 19 September to 29 October, /13 the velocity vector of the probe can be increased or reduced vectorially by the quantity 19.5 or 18 km/sec at maximum, respectively, after a flying time of 600 days. If the pericenter distance of the swingby hyperbola for this example were increased from 1 Jupiter radius to 1.5 Jupiter radii, the maximum quantity would be reduced by only about 500 m/sec. As was indicated by Figure 5, the response of ΔV_{\max} to variation of the pericenter distance was substantially greater. The implication is, however, that for technologically easier transfer trajectories to Jupiter a slight error in the pericenter distance should not have a very unfavorable effect on the further secondary mission.

With the extremely short transfer of 340 days, the probe would be accelerated or decelerated by between 36 and 34 km/sec, respectively, for the same launch dates in 1978.

3. UTILIZATION OF THE JUPITER GRAVITY FIELD FOR INTERPLANETARY MISSIONS

The further objective of this paper is to provide a conspectus of precisely defined missions that pass Jupiter at an exactly calculated distance in an exactly calculated direction. The deflection occurring in the sphere of influence in the primary undisturbed probe trajectory then directs the spacecraft to the actual objective of the whole mission on the new secondary trajectory.

The objectives that thus become accessible to unmanned space flight in the last third of our century can be outlined as follows (Fig. 7):

Objectives in the Trans-Jovian Region of the Solar System

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Exploration of the outer planets (individual missions).
Mission to the outer planets with a spacecraft ("Grand Tour").
Exploration of the peripheral regions of the solar system
(comet clouds).

Objectives in the Cis-Jovian Portion of the Solar System

Exploration of solar phenomena in the ecliptic close to the sun.
Exploration of the sun outside the ecliptic (high heliographic latitudes).
Exploration of the out-of-ecliptic region of the inner solar system (asteroid mission).
Exploration of short-period comets.

Figure 7 shows a conventional diagram of the trajectory profile pertaining to these missions.

In what follows, it is attempted to give a summary of the most important results of analytical studies of interplanetary missions with Jupiter swingby on the basis of the available literature and in accordance with the above classification.

3.1 Objectives in Trans-Jovian Space

Beyond the orbit of Jupiter, the objects of primary interest for research are the planets Saturn, Uranus, Neptune, and Pluto with their satellites; the Oort comet cloud at the edge of the solar system at a distance of about 50,000 AU to 100,000 AU; and the planet system of the nearest fixed star at a distance of 4.3 light years.

3.11 Saturn Missions

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The next objective beyond Jupiter will be the planet Saturn. It differs from all other planets in having the lowest density, 0.7 g/cm^3 , and the greatest flattening, 1:10. The planet exhibits a banded structure similar to that of the planet Jupiter. A conspicuous feature is white spots in the atmosphere that exhibit a rapid change of shape. They are probably caused by eruptions from the interior or by outgassing of H_2 .

A unique phenomenon in the solar system are the rings of Saturn. The three rings, A, B, and C, rotate in keeping with Kepler's third law. The question of whether the rings consist of ice crystals or dust particles has not been solved. Another question of interest is whether the ring was produced from a moon of Saturn that was disintegrated by tidal forces or whether it is the residue of interplanetary matter that was left over from the formation of the planet. Another important object for research in the Saturn system is Titan, the largest moon of Saturn, which is of roughly the same size as the planet Mercury and has an atmosphere consisting of heavy gases.

The primary aspect of orbital mechanics to be investigated is the relation between the flying time (Earth-Jupiter-Saturn), the geocentric excess speed, the launch date, and the minimum distance from Jupiter during the passage. Detailed studies in this field were carried out by Niehoff [1], Deerwester [2], and Flandro [3]. While Niehoff assumes an ideal solar system (planets moving in coplanar central orbits in the ecliptic, excepting Mercury), Deerwester and Flandro have made allowance for the actual ephemerides. These two authors arrive at the following results (Fig. 8).

Diagram (a) shows the variation of the total flying time as a function of geocentric excess velocity for different launch dates with r_{\min} as the parameter. Direct transfer trajectories to Saturn are plotted for comparison (launch in 1977). Direct trajectories with a flying time of about six years are particularly unfavorable on energy grounds, since these trajectories require a high inclination to the ecliptic (the transfer angle is then about 180°). In 1976, the minimum launch energy of v_H of about 0.31 EMOS would be necessary; in this case, the minimum distance from Jupiter would have to be 1.5 Jupiter radii. The total flying time, however, is very long, being close to 5 years. /16

The most favorable direct mission to Saturn in 1977 would have a flying time of about 4 years. It would require a hyperbolic excess speed at launch of about 0.385 EMOS. If the trajectory of the probe is carried past the center of Jupiter at a distance of about 10 planet radii, however, only about 0.32 EMOS will be needed at launch for the same total flying time. Thus, the saving as a result of the swingby maneuver is of the considerable order of 2 km/sec, a clear advantage of the technique. Furthermore, the diagram also indicates that for extremely short missions of about 2 years in 1977-1979 and later, direct missions entail the same values as secondary missions. In fact, it has been found that for later launch dates the direct missions are superior to the swingby missions by the criteria of time and energy.

The schematic profile of a transfer trajectory is plotted in Diagram (b). The launch takes place in September 1977. The required geocentric hyperbolic excess velocity is 0.35 EMOS. Jupiter is flown by at a distance of 3 planet radii. The heliocentric velocity of the probe is increased vectorially by 18.7 km/sec. A marked deflection of the undisturbed Earth-Jupiter trajectory is noted. Saturn is reached after a total flying time of 1072 days. /17
Other favorable launch dates are July-August 1976 and October 1978, in the first week of October as reported by Flandro [2].

3.12 Uranus Mission

The spectrum of this planet shows that methane, a large quantity of hydrogen, and helium occur in the atmosphere. This planet exhibits a peculiarity as compared to the other outer planets. Its axis of rotation is almost in the orbit plane, which exhibits an

inclination to the ecliptic of less than 1° . The five moons discovered thus far move almost in the plane of the equator, hence perpendicular to the orbit plane.

The trajectory profile and the mission parameters were studied in depth by Flandro and Deerwester. The results can be seen in Figure 9. Diagram (a) shows the shape of the trajectory; Diagram (b) indicates the following, for example. If a launch energy of about 0.34 EMOS is selected, a mission with a total flying time of about 6.5 years can be started in 1978 and 1979, although for 1978 the spacecraft would have to come within about 2 planet radii of Jupiter whereas for 1979 only about 12 planet radii would be required. As the two curves show, the launch dates in 1978 and 1979 are roughly equivalent with respect to propulsion energy at launch and flying time. However, since in 1978 substantially smaller distances from Jupiter must be scheduled, from 1 to 7 planet radii, preference is to be given to the year 1979, in which for flying times under 5 years Jupiter must be approached within 5 planet radii at the most and for extremely long missions of about 10 years only about 25 planet radii would be required.

The shape of the curve for direct transfer trajectories in 1979 indicates the great advantage of the gravity field of Jupiter for the execution of missions to Uranus. It indicates that the most favorable launch date in 1979 would require a flight of 12 years with a launch energy of 0.38 EMOS. With Jupiter swingby (launch in 1978), only about 10 years with 0.32 EMOS would be necessary. If the flying time for either mode was scheduled as 6.5 years, 0.42 EMOS would have to be provided for the direct mission, but for the indirect (launch in 1978 or 1979), only 0.34 EMOS. The result would be a saving in the former case with long missions of 1.8 km/sec, and in the latter case with relatively short flying times, a saving of 2.6 km/sec.

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From the papers published by Flandro [2], for a specific launch year the most favorable launch date can be determined within a launch window of 30 days for varying launch energies from 10.5 km/sec to about 14.2 km/sec, for missions to all the trans-Jovian planets.

For example, for the year of this mission in 1978 with an excess velocity of 0.35 EMOS, the most favorable launch date in the period from 25 September to 23 October would be 6 October. Furthermore, the diagrams published by Flandro permit determination of the transfer times from Earth to Jupiter. Unfortunately, the diagrams provide no direct information on the respective minimum distances from Jupiter, however.

3.13 Neptune Missions

This planet does not differ substantially from Uranus with respect to its density and to the constitution of its atmosphere. The

numerical data that now can be stated for its physical properties are subject to rather great uncertainty. However, the reliable aspect is the existence of two satellites, the larger of which (Triton) has a retrograde orbit around the planet. /19

The velocity requirement for a Neptune mission with Jupiter swingby was computed by Deerwester [3] and Flandro [2] as a function of flying time and launch date. Figure 10 shows the results. The profile of the Earth-Jupiter-Neptune trajectory can be seen in Diagram (a). The launch from Earth would have to take place in November 1979. If the launch energy is limited to about 0.37 EMOS, the optimum launch date as reported by Flandro would be about 10 November. The flying time - see Diagram (b) - would then be about eight years. In that case, the probe would have to fly by the planet Jupiter at a distance of about 3 planet radii. Diagram (b) also indicates that 1979 is the optimum launch year for Neptune missions with Jupiter swingby when the launch energy and total flying time are considered. In 1978, very close Jupiter rendezvous would be necessary. The launch year 1980 is roughly as favorable as 1979 for a flying time of about 8 years. The distance from Jupiter then could be increased to about 9 planet radii. For comparison, Diagram (b) also contains direct Earth-Neptune trajectories. If a transfer time of eight years is also selected for this mode, a propulsion energy of 0.48 EMOS would be required, an increase of 3.3 km/sec as compared to the above-mentioned mission in 1979 with Jupiter swingby. If the flying times are compared and the launch energies for both modes are held constant at about 0.39 EMOS, the direct trajectory would require 24 years, 17 years more than the "disturbed" trajectory.

3.14 Pluto Missions

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Present information on this planet is limited and much disputed. The most conspicuous features are its orbital parameters as compared with those of other planets. Its orbit has the greatest inclination to the ecliptic (17°) and the highest eccentricity (perihelion, 30 AU; aphelion, 50 AU). The origin is a matter of great controversy. Some astronomers deduce that it is a fugitive satellite of Neptune; others trace its origin outside our solar system. In the latter event, it could have been captured by the gravity field of Jupiter.

Deerwester and Flandro have reported the following information on the mission parameters and the shape of the trajectory (Fig. 11).

Diagram (a) shows that the rendezvous with Pluto occurs in the vicinity of its perihelion (30 AU), hence within the average distance to Neptune; Diagram (b) indicates that the most favorable launch dates for Pluto missions are to be found in the year 1977. To cite an example, the mission would last 10 years with a geocentric hyperbolic excess velocity of 0.34 EMOS. The minimum distance from the center of Jupiter would have to be 5 planet radii.

The great importance of the planet Jupiter for advanced inter-

planetary missions to the outer solar system emerges most spectacularly with a Pluto mission as the example, as shown by the comparison of the direct transfer trajectories to Pluto with trajectories accelerated by Jupiter swingby in Diagram (b). Even a direct trajectory of v_H equal to about 0.48 EMOS would have a flying time of 38 years; slower probes (v_H about 0.38 EMOS) would be traveling even 44 years.

With the above-mentioned swingby mission of the year 1977, the total flying time and the hyperbolic launch velocity are reduced by 34 years and 1.2 km/sec, respectively. /21

3.15 Multiple Swingby in Gravity Fields ("Grand Tour")

When all the individual missions, from that to Saturn to that of Pluto, are compared, the average flying times are noted to be 4 to 12 years. The average launch speeds are in the order of magnitude of 0.34 EMOS (10.2 km/sec). The implication is an unusually high technological and economic commitment for the exploration of the entire outer solar system (including Jupiter) on the basis of individual missions.

Therefore, the obvious inference was to combine individual missions to the outer planet into a single mission on the basis of the possible speed gains as a result of the gravity fields of Jupiter, Saturn, and Uranus (see Fig. 4). The studies of multiple successive deflections of a probe trajectory as a result of the attractions of the outer planets by Deerwester and Flandro have shown that an entire category of such missions will indeed be possible in the second half of the eighth decade.

Figure 12 shows important results of those studies. In Diagram (a), the trajectory plotted is that of a mission that would have to be launched on 14 September 1977. The characteristic launch speed is $v_H = 0.33$ EMOS. Jupiter is reached after about 2 years. The scheduled swingby requires a distance of 12 Jupiter radii from the center of mass. Saturn is reached after another two years on 12 December 1981. The probe must pass this planet on the night side at a distance of only 3.4 Saturn radii. As can be seen, the trajectory undergoes its greatest deflection in the sphere of influence of Saturn.

Uranus is passed almost 5 years later on 31 July 1986, on the day side at a distance of 6 Uranus radii. The rest of the mission also lasts 4 years, with the result that the planet Neptune is reached on 23 May 1990. Hence, the entire mission requires about 12 years and 8 months. Thus, the propulsion energy and flight duration are equivalent to the values for individual missions to Neptune. If it is assumed that the swingby maneuvers can be executed within admissible errors, such a triple swingby mission offers a means of exploring the four large planets of the outer solar system with a single spacecraft. /22

The optimum launch date for similar missions which, however, begin in 1978, can be taken from the diagram of Flandro. The launch energy ($C_3 = v_H^2$) must be restricted to values between 90 and 130 km^2/sec^2 . As Flandro states, higher launch energies are not possible, since otherwise the minimum distance from Saturn would become too small to permit subsequent flight to Uranus. Owing to the large deflection by Saturn, the launch dates in 1977 are also restricted to $90 < C_3 < 120 \text{ km}^2/\text{sec}^2$. With a hyperbolic launch velocity of 0.37 EMOS ($C_3 = 120 \text{ km}^2/\text{sec}^2$), the entire mission lasts 8.9 years if the launch occurs on 7 October 1978.

3.2 Launch Opportunities

To sum up, it can be stated that an entire category of launch opportunities are found in the second half of the 70's for exploration of the outer planets, including Jupiter, by means of secondary missions (Jupiter swingby). The following conspectus is given by Flandro (Table 2).

TABLE 2. POSSIBLE SECONDARY MISSIONS (AFTER FLANDRO [2])
(THE INDEXED YEARS CONTAIN THE OPTIMUM LAUNCH DATES)

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Mission	Launch Years				
Earth-Jupiter-Saturn-Escape	1976	1977	1978 ⁺		
Earth-Jupiter-Uranus-Escape	1977	1978	1979 ⁺	1980	1981
Earth-Jupiter-Neptune-Escape	1977	1978	1979 ⁺	1980	1981
Earth-Jupiter-Pluto-Escape	1975	1976	1977 ⁺	1978	1979
Earth-Jupiter-Saturn-Uranus-Neptune	1976	1977 ⁺	1978		

It is noteworthy that in the simple secondary missions, the probes undergo an acceleration through the deflection by the target planet that carries them out of the solar system.

The mission parameters in Table 3 hold good for the optimum simple swingby missions, according to Flandro.

It is of high importance to know the time interval in which the launch opportunities are approximately repeated. The corresponding parameter of the interval is the synodic period of the trans-Jovian planets, referred to the sidereal period of revolution of Jupiter. This time parameter gives information as to when an arbitrary relative position (measured in heliocentric longitude) of the outer planets with respect to the position of the planet Jupiter, referred to the vernal equinox, will recur.

According to the studies by Deerwester [3], there is a relation between the relative longitude of the outer planets, referred to the longitude of Jupiter, and the number of the year, which can be used to derive the cycle in which simple secondary missions with Jupiter swingby can be repeated.

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TABLE 3. OPTIMUM SWINGBY MISSION TO THE OUTER PLANERS
(AFTER ELANDRO [2])

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	Launch Energy C3 [km ² /sec ²]	Optimum Launch Date	Flying Time (Days)	Peri- jovion (Jupiter Radii)	Deflec- tion (deg.)	HEV at Jupiter [km/sec]	Energy Gain [km ² /sec ²]	Speed Gain [km/sec]
Earth-Jupiter-Saturn	150	11 Oct. 78	838	7.37	56.8	16.42	192	14.70
Earth-Jupiter-Uranus	130	11 Oct. 78	1957	1.17	127.2	14.26	227	17.38
Earth-Jupiter-Neptune	150	12 Nov. 79	2525	3.50	80.8	16.68	241	18.45
Earth-Jupiter-Pluto	150	8 Sept. 77	2530	2.93	88.7	16.23	251	19.22

The approximate cycles are the following:

Earth-Jupiter-Saturn	Every 20 years
Earth-Jupiter-Uranus	Every 14 years
Earth-Jupiter-Neptune	Every 13 years
Earth-Jupiter-Pluto	Every 13 years

The implication is that the next optimum mission to Uranus would not be possible until 1993.

The favorable launch opportunities for the Earth-Jupiter-Saturn-Uranus-Neptune triple swingby missions are substantially smaller in number. For the "Grand Tour" mission, this period is about 175 years. Why this should be so can be visualized roughly by considering the orbital periods of the respective planets (Jupiter, 11.9 years; Saturn, 29.5 years; Uranus, 84 years; and Neptune, 165 years). In general, the frequency of repetition of the most favorable dates for missions with multiple swingby maneuvers* will increase with increasing difference between the sidereal period of the planers involved.

3.3 Objectives in Cis-Jovian Space

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In interplanetary space between the sun and the orbit of Jupiter, objectives of scientific research are, very briefly, the following: the region far outside the zodiac - that is, at a great distance from the ecliptic; the asteroids in high heliocentric latitudes; meteorite swarms; the sun and its immediate vicinity within and outside of the ecliptic; and bodies that exhibit special properties in the vicinity of the sun, such as comets.

*TRANSLATOR'S NOTE:Error in original text.

3.31 *Exploration of the Sun*

The discovery of the mechanism by which the numerous solar phenomena take place in the different layers of the sun, such as the photosphere, chromosphere, and corona, is one of the most urgent objectives of interplanetary space flight for the near future. Even as observed from the Earth, several phenomena exhibit a clear dependence upon the heliographic latitude (inclination of the equator of the sun, 7°), such as flares, sunspot groups, prominences, and certain details of the corona, to mention only a few (for particulars, see [4]). According to Reference [4], it is necessary to perform direct measurements of the plasma, magnetic field, and radiation above the activity centers in high heliographic latitudes.

The result in any case is the need to launch at least two solar missions. As substantiated in detail in Reference [4], a perihelion distance of more than 0.3 AU seems rather pointless as far as the quality of the responses to the experiments is concerned. The first mission should take place nearly in the ecliptic, whereas the trajectory of the second mission should have an inclination of about 90° to the ecliptic.

In what follows, the propulsion energy requirement and the duration of such missions will be discussed.

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3.311 *In-Ecliptic Solar Missions*

As Figures 1 and 2 indicate, the gravity field of Jupiter cannot only accelerate a probe, but also decelerate it. As a result, there are two basic means of executing missions for exploration of the sun. The first group comprises the missions whose trajectory leads into the inner solar system directly after launch from Earth; the other group comprises the trajectories that first are deflected by Jupiter and then carry the probes close to the sun in or out of the ecliptic. In Figure 13, the geocentric hyperbolic excess velocity has been plotted as a function of the required perihelion distance and inclination to the ecliptic. The orbital periods of these trajectories were also plotted. The numerical eccentricity of the Earth orbit was neglected in the plot.

If only in-ecliptic trajectories are considered at first, a considerable increase of the excess velocity is noted for perihelia smaller than 0.3 AU. From 0.3 AU to 0.2 AU, the increase is 3.1 km/sec.

Figure 14 shows the flying time as a function of propulsion requirement, with the resulting perihelion as the parameter, for in-ecliptic solar probes exploiting the gravity potential of Jupiter, as reported by Niehoff from his studies [1]. The parameter was introduced in the form of the pericenter distance (measured in planet radii) of the swingby hyperbola. The two types of missions can be compared with reference to a specific example. Let the target peri-

helion be 0.3 AU. The required excess velocity for the direct mission then will be 0.32 EMOS. An orbit on this ellipse would last about 190 days. The same propulsion requirement would provide a trajectory to Jupiter. If the perijovion of the hyperbola is about 9 Jupiter radii, the trajectory will be deflected and decelerated to produce a perihelion of 0.3 AU after a total flying time of about 3.33 years. Figure 14 shows that the propulsion requirement can be decreased further, however, if the penalty of longer flying times is accepted. With a flying time of 3.8 years, the excess velocity is reduced to 0.31. The diagram indicates further that if, for example, a transfer trajectory to Jupiter is adopted with a flying time of 500 days, characterized by $v_H = 0.34$ EMOS, the result for $r_{min} = 2$ with a total flying time of 2.85 years will be a perihelion of 0.3 AU. Next, in order to obtain smaller perihelia with a constant propulsion requirement, Jupiter must be swung by at a greater distance. In this case, the flying time increases. Thus, with $r_{min} = 5$ the result is a perihelion of 0.1 AU. The flying time is prolonged by about 40 days in this case. This tendency becomes understandable if the jovicentric excess velocity and the angle between the asymptotes of the swingby hyperbola are determined as a function of the perijovion. It is then found that the heliocentric velocity of the probe will be inversely proportional to the minimum distance during the swingby. This relation holds good for a certain range that depends upon the starting values for the jovicentric phase. For the heliocentric orbital parameters after swingby, as compared with those before the perturbation, a decrease of the aphelion and perihelion distances is found. The cause of the increase in flying time from the Jupiter rendezvous to the new perihelion is the marked deceleration of the probe. /28

If the perihelion is to be held constant, a decrease of the perihelion is possible only by means of Earth-Jupiter transfer trajectories of shorter flying time, entailing a higher propulsion energy. The optimum path for bringing the probe closer to the sun runs along the gradients of the family of curves (the gradient determined by the values $v_H = 0.34$ EMOS, $r_p^+ = 0.3$ AU was plotted in the diagram). Accordingly, with $r_{min} = 5$ the result is a perihelion of 0.005 AU (diameter of the sun), while the flying time and propulsion requirement are increased by only about 40 days and 0.01 EMOS, respectively. If the propulsion requirement were less constant at 0.34 EMOS, this close approach to the sun could not be achieved, and with the perijovion constant at 2 planet radii it would be necessary to increase the geocentric hyperbolic excess velocity to 0.38 EMOS. /29

If it were intended to reach a perihelion distance of 0.02 AU on a direct mission, an excess velocity of 0.8 EMOS would have to be supplied. By means of the gravity field of Jupiter, this quantity is reduced to 0.35 EMOS, by the equivalent of 56%.

A good graphical summary of the astrodynamic possibilities for executing in-ecliptic solar missions is provided by the next diagram

(Fig. 15), given by Niehoff [1]. The ordinate is geocentric hyperbolic excess velocity (called "ideal velocity" by Niehoff); the abscissa, the perihelion distance. It compares missions with swingby around Venus to missions employing swingby maneuvers around Jupiter and to direct missions. For the Jupiter missions, the respective flying time is introduced as the parameter. For the other missions, the respective flying time is noted on the curves. The diagram indicates very plainly that from the point of view of propulsion requirement, up to a perihelion of about 0.2 AU it is rather pointless to execute a Jupiter rendezvous, since in these cases the flying time becomes about a factor of 10 as great as that of the direct and Venus swingby missions. For extremely small perihelion distances, however, the saving in propulsion requirement through the Jupiter gravity assist is striking. It is also noteworthy that the propulsion requirement for a given flying time is nearly independent of the perihelion of the probe trajectory after the Jupiter swingby. This result can also be interpreted to mean that owing to the high attraction of Jupiter a slight variation of the starting values for the jovicentric phase causes great changes in the heliocentric orbital parameters.

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3.312 Out-of-Ecliptic Solar Missions

It has been stated further that there is a scientific need for out-of-ecliptic solar probes with an inclination of the orbit plane of about 90° . Figure 14 indicates that owing to the unusually high propulsion energies direct missions will not be possible, since an excess velocity of at least 1.0 EMOS is required, regardless of the perihelion distance. With increasing inclination, the tendency for greater perihelion distances to require more energy than smaller ones can easily be explained. It is due to the fact that more energy (hyperbolic excess velocity) is required for the deflection (inclination) of a velocity vector (aphelion velocity of the probe) of large magnitude than is required for the deflection of a vector of smaller magnitude.

In this case as well, the only recourse remaining is the gravity potential of Jupiter. According to the studies by Metzger [5] and Minovitch [6], in order to obtain arbitrary inclinations of the probe orbit plane after the Jupiter encounter, the magnitude of the hyperbolic excess velocity of the probe upon entering the sphere of influence of Jupiter must be greater than or equal to the heliocentric velocity of the planet. That will be the case if the transfer times from Earth to Jupiter (assuming tangential trajectories) are 450 days at the most. It is easy to show that a maximum inclination of about 25° can be obtained through Hohmann transfer.

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Extensive studies to discover the relation between the orbital parameters of the undisturbed Earth-Jupiter transfer trajectory and the parameters of the trajectories after the swingby maneuver were carried out by Metzger [5]. A brief excerpt of these results is found in Figures 16 and 17. Figure 16 shows the profile of a

mission trajectory in a perspective diagram. The launch date chosen was 26 July 1975.

The required excess velocity is 0.37 EMOS. The Earth-Jupiter transfer trajectory lies practically in the ecliptic ($i = -1.4^\circ$). The encounter with Jupiter takes place after 450 days at a distance (perijovion) of 7 Jupiter radii. As a result, the probe is deflected 90° out of the ecliptic. The new perihelion that comes about is equal to 0.045 AU. The entire mission lasts 3.14 years from launch to the point closest to the sun. The passage through the asteroid belt lasts about 200 days on the flight to Jupiter and another 200 days on the way from Jupiter to the sun.

Figure 17 shows the possibilities resulting from a mission to Jupiter with launch on 17 June 1975 and a flying time of 450 days. The propulsion requirement is 0.38 EMOS in this case. The inclination of the orbit plane after swingby was plotted as a function of total flying time from the launch on Earth to arrival at the perihelion. The parameters are the perihelion distance and the perijovion distance of the swingby hyperbola. The minimum distance was varied between 11 and 5 planet radii. The range of inclinations examined is restricted to values between 85° and 110° . The family of curves of the perijovia was extrapolated for inclinations greater than 103° .

The diagram indicates that if an inclination of 90° and a perihelion of less than 0.1 AU are required, two ranges of solutions will be obtained. The first range supplies relatively short flying times of 1060 days to 1120 days. The perijovion then varies between 5 and 6 Jupiter radii. The resulting perihelion distance is as small as about 0.005 AU. The second range is situated between $r_{\min} = 9$ and 11 Jupiter radii. In this case as well, the approach can be as close as the radius of the sun, 0.005 AU. Then, however, the result would be rather long total times, from about 3.6 years to 3.9 years. The second range of solutions corresponds in trend to the results discussed above for out-of-ecliptic solar missions with Jupiter swingby. /32

In the case of out-of-ecliptic missions for exploration of the sun, it will be necessary to execute the swingby maneuver in a mode that will greatly decelerate the probe. The perihelion, the aphelion, and the semiminor axis will be reduced thereby. In the example shown in Figure 16, this axis is equal to only about 0.46 AU. This, however, implies that such missions are unsuitable for exploration of the high out-of-ecliptic region of the inner solar system. In order to study the scientific objectives at great distances from the ecliptic, such as meteorite swarms, the plasma, and the magnetic fields, the rendezvous with Jupiter must be executed in a mode that will deflect the probe 90° out of the ecliptic but provide less deceleration or acceleration. Such missions have been studied, for example, by Porter [7]. For all missions to explore the sun and cis-Jovian space without any specific body (asteroid or

comet) as the objective, launch opportunities recur roughly with the synodic period of Jupiter, about 13 months.

3.32 Missions to Comets

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The third prominent objective within the inner solar system that can be reached with a Jupiter gravity assist is a rendezvous with comets.

Valuable clues to an understanding of the genesis of the solar system are expected from comet exploration with spacecraft. Furthermore, comets can be regarded as indicators of solar activity: conclusions about the activity of the sun can be drawn from the intensity of cometary phenomena.

The most interesting object for comet research in the next 20 years will be Halley's Comet, whose latest perihelion passage was observed in 1910 and whose return is predicted for 1986. This comet surpasses others because of its small perihelion distance (0.59 AU), its size (absolute brightness, $m_0 = 4.6$), and the retrograde direction of its orbit (inclination, 162°).

The primary reason for the high importance of rendezvous missions is that it is then possible to study the variation of the phenomena of the core, coma, and tail as a result of the varying distance from the sun.

Narin, Roberts and Pierce [8] have developed direct mission profiles for a great many short-period comets.

The most important mission parameters of a flyby mission to Halley's Comet are compiled in Table 4, based on those studies.

TABLE 4. DIRECT MISSIONS TO HALLEY'S COMET (AFTER [8])

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Perihelion passage	8 January 1986	
Launch of the probe	January 1985	July 1985
Flying time (days)	300	210
Geocentric excess velocity (EMOS)	0.44	0.43
Relative velocity of the probe at rendezvous (EMOS)	2.18	2.32
Earth-probe distance at rendezvous (AU)	0.5	1.25

A conspicuous feature is the unusually high relative velocities of the probes (referred to a coordinate system connected with the comet). They come about primarily because the vector direction of the comet is opposite to that of the probe. Therefore, a rendezvous seems impossible with the present capacity of chemical rocket engines.

In this case once more, the utilization of the Jupiter swingby

mode lends itself as a recourse. This possibility has been studied in greater depth by Michielsen [9]. (Since the original paper was not available when this manuscript was being prepared, only the qualitative description of this comet mission with Jupiter swingby as given in Reference [10] can be reported here.)

As reported, the launch from Earth takes place at the end of 1977. The propulsion requirement corresponds to an excess velocity of about 0.47 EMOS. After a relatively short flying time to Jupiter, the probe flies into the inner solar system on a trajectory whose plane is inclined about 160° to the ecliptic. As a result, the vector direction of the probe becomes retrograde in the astronomical sense, thus corresponding to that of the comet. The rendezvous then takes place at about 3.8 AU roughly 200 days (July 1985) before the perihelion passage of the comet (5 February 1986). To be able to execute the rendezvous, the probe would have to increase its own heliocentric velocity. At this point on its orbit, the velocity of the comet is about 0.74 EMOS. The relative velocity increment that would have to be supplied by the probe propulsion has been computed as 0.21 EMOS. In sharp contrast thereto, the direct mission would require an increment more than a factor of 10 as great. /35

These remarks have concluded the discussion of possible interplanetary missions with Jupiter gravity assists.

4. SUMMARY AND CRITIQUE

The discussed examples of missions indicate clearly the great importance of the astrodynamic "finesse" of the Jupiter swingby mode for the exploration of the solar system with spacecraft. Special mention was made of the reduction of the propulsion requirement for free-flight trajectories to the respective objects that become feasible when perturbation of the trajectory in the Jupiter gravity field is utilized. Furthermore, the results indicated the variation of the flying time: reduction for missions into the trans-Jovian region; prolongation in missions into the inner solar system.

Such complicated missions, however, raise quite a number of problems which must at least be touched upon in a brief review in this connection, since mastery of the propulsion problem alone is not conclusive for the success of a mission.

Three mission criteria can be defined for the classification of the individual problems: scientific tasks, trajectory accuracy, and mission duration. /36

Scientific Tasks

Besides the investigation of the Jovian phenomena, the utilization of the swingby mode *around Jupiter* opens up quite a number of objectives that can be reached only with extraordinary difficulty or not at all by direct missions with the present launch vehicles:

the planets Saturn, Uranus, Neptune, and Pluto, and in the inner solar system, solar phenomena in high and low heliographic latitudes and extremely close to the sun; and, finally, the regions far outside the ecliptic. Several objectives can be investigated on a single mission (for example, the "Grand Tour"). The instrumentation can be used for several objects of research: for example, the radiation belt of Jupiter can be investigated with the same instruments as the radiation of solar origin. Consequently, the number of instruments is not proportional to the number of objectives.

The gain from a few scientific experiments is restricted by the high perihelion velocity of trajectories with a perihelion distance of about 0.1 AU and less. For example, its value for the mission shown in Figure 16 is about 200 km/sec: the probe remains only about 10 days at a range of 0.3 AU.

Unusually great problems will be presented, among others, by the extreme heat stress. Near Jupiter, minimum temperatures of about 100° K can occur on the probe; close to the sun (0.1 AU), heat shields for about 1000° K would have to be extended.

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Mission Duration

As compared with the direct missions, the swingby mission for exploration of the inner solar system has the plain drawback of substantially greater flying times until the actual objective is reached. They result in increased demands on the reliability of functioning of the technological components. The asteroid belt is traversed twice. The risk of a collision between the probe and small bodies is doubled. Solar-cell power supplies for position adjustment and data transmission are not adequate over the great distances, and for distances of about 2 AU and more they must be replaced by power supplies based on nuclear energy (radioisotope generators). The flying times to the trans-Jovian planets are reduced and, hence, the resulting problems as well.

Trajectory Accuracy

The greatest demands on the course correction system are presented by the secondary missions to the outer planets, particularly by the "Grand Tour." As the theoretical studies by Metzger [5] indicate, slight changes of the heliocentric vector of the probe shortly in advance of the jovicentric phase caused considerable variation of the trajectorial parameters. Exact computations of the fuel requirement for these course corrections have not become known for the missions under discussion. It is rather likely that the magnitude of these fuel loads will not become as critical as the need to ignite these engines more often than on the missions executed thus far, since in addition to the injection errors in the transfer from the geocentric phase to the heliocentric, and in addition to the uncertainty in the astronomical constants of the outer planets including Jupiter, small errors of the velocity vector will affect

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the trajectory accuracy (position and shape of the swingby hyperbola), owing primarily to the large distances; the study by Metzger [5] plainly indicates that a high trajectory accuracy is required in the vicinity of Jupiter. The trajectory accuracy is less of a problem for the solar missions with Jupiter swingby. Although the magnitude of the launch velocity has been found to have a great influence on the resulting perihelion, errors in the injection velocity are less detrimental from a certain threshold upward, since the experiments will be little affected by whether the probe approaches within 0.1 AU or 0.05 AU of the sun. The heliocentric longitude of the perihelion will also play no important part.

These intimated engineering problems imply the need for sufficient redundancy in order to obtain a high reliability. The required payloads could in any case be launched by the Saturn V launch vehicle or the Saturn I B in combination with suitable upper stages. An estimate of the payload capacity of launch vehicles for interplanetary missions can be obtained from Figure 19, based on References [14] and [15].

The fact that mastering the above-mentioned difficulties essentially does not require any new developments is to be assessed positively. Therefore, there is hope that these ambitious space flight missions of the second generation can be implemented by extending and improving the criteria and systems already known.

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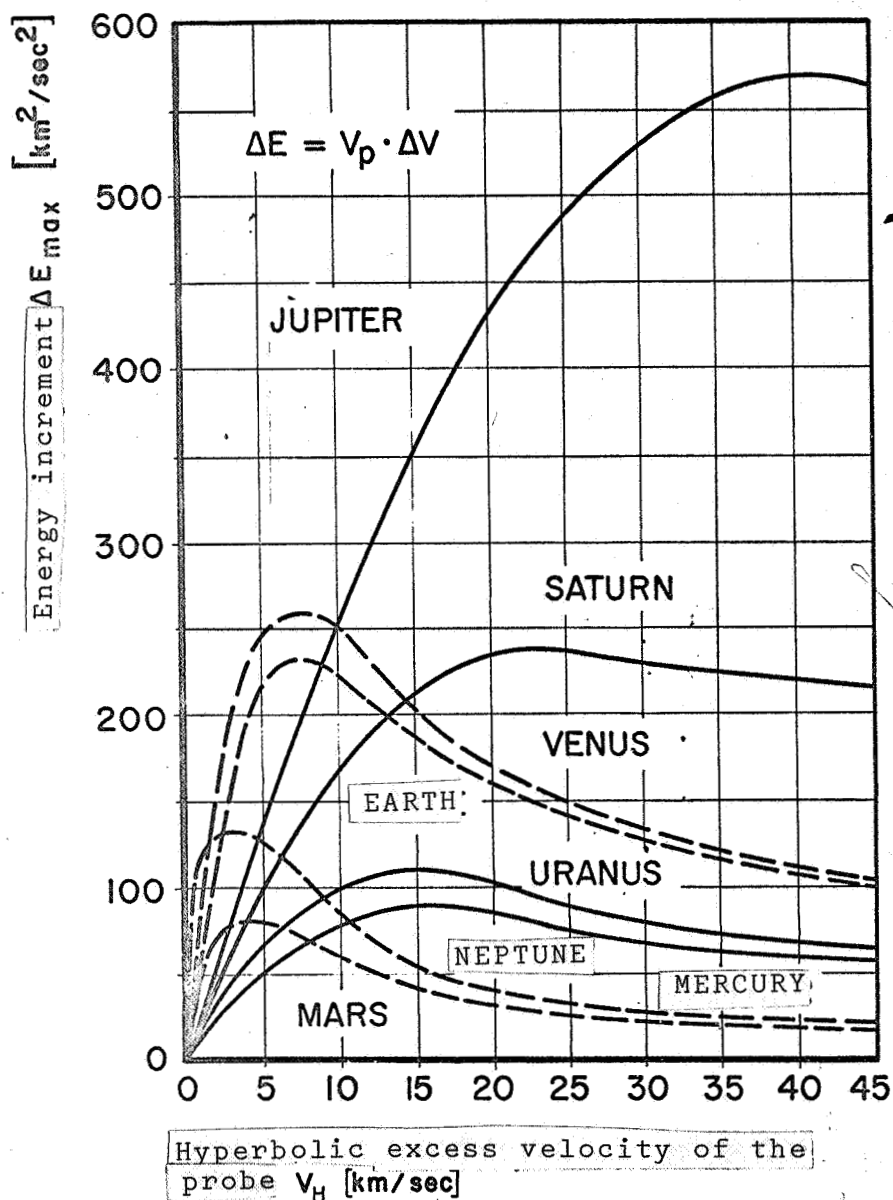


Fig. 3. Maximum Energy Increment of a Probe in the Gravity Fields of the Planets (after Flandro [2]).

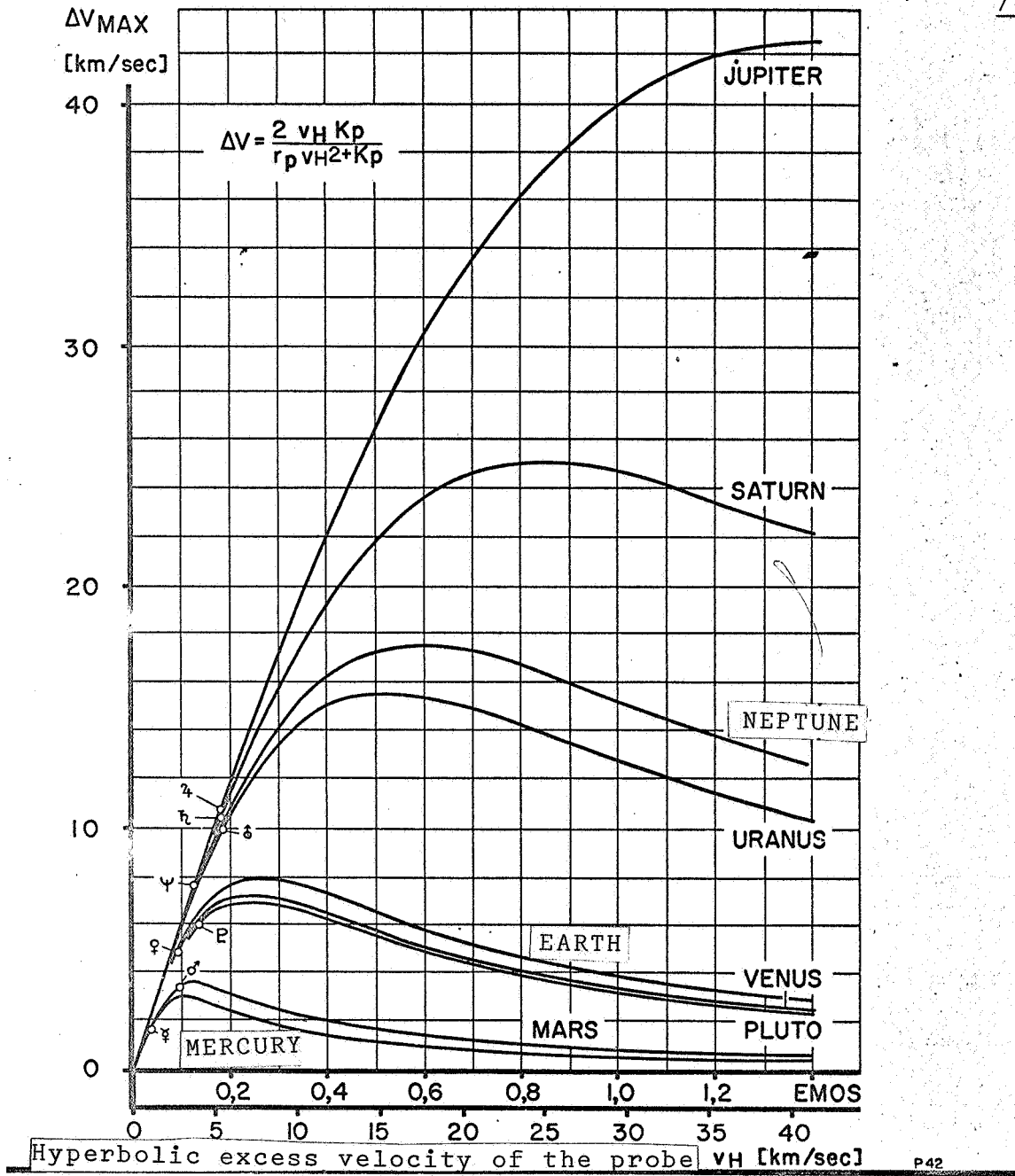


Fig. 4. Maximum Velocity Increment of a Probe in the Gravity Fields of the Planets.

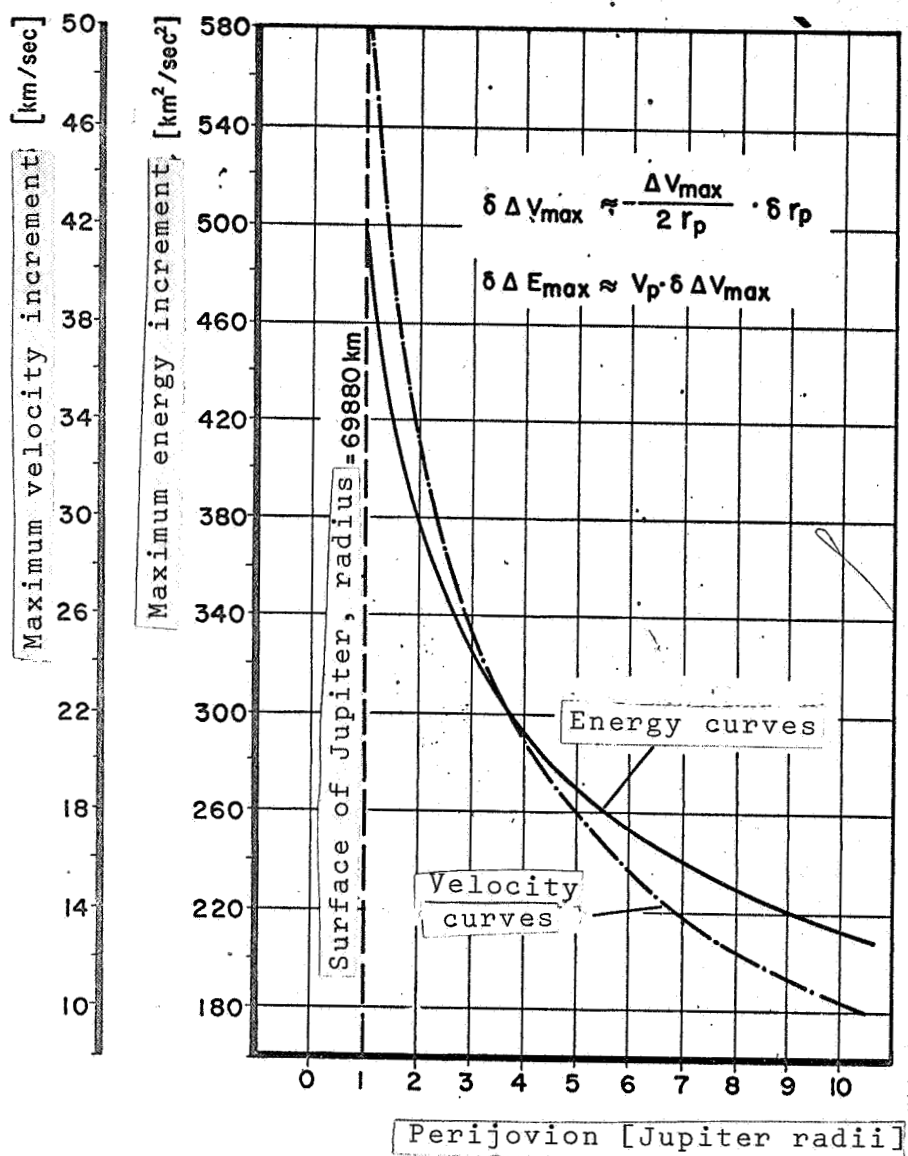


Fig. 5. Variation of ΔE_{\max} and ΔV_{\max} by Variation of the Perijovion (after Hiehoff [1]).

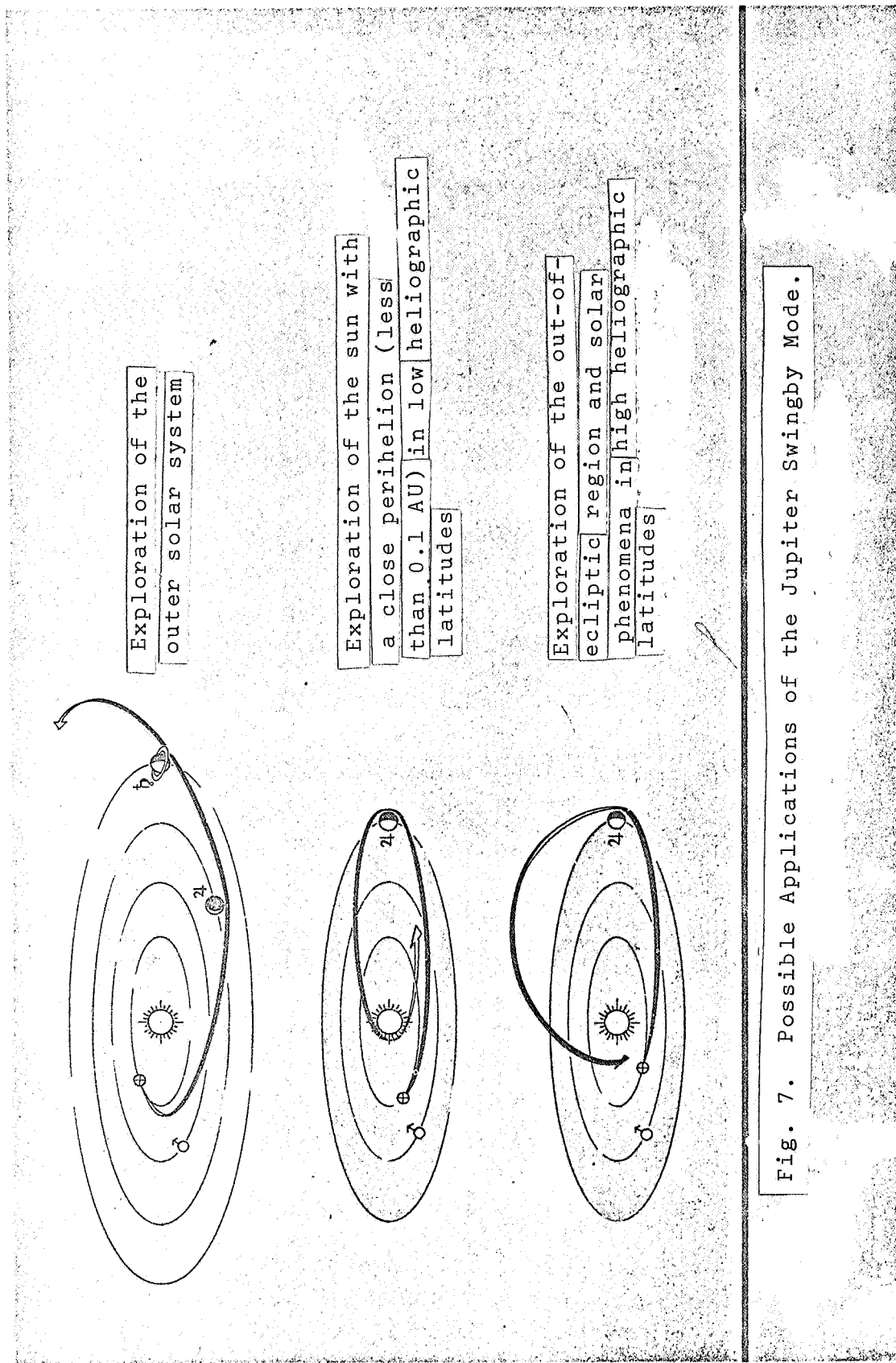
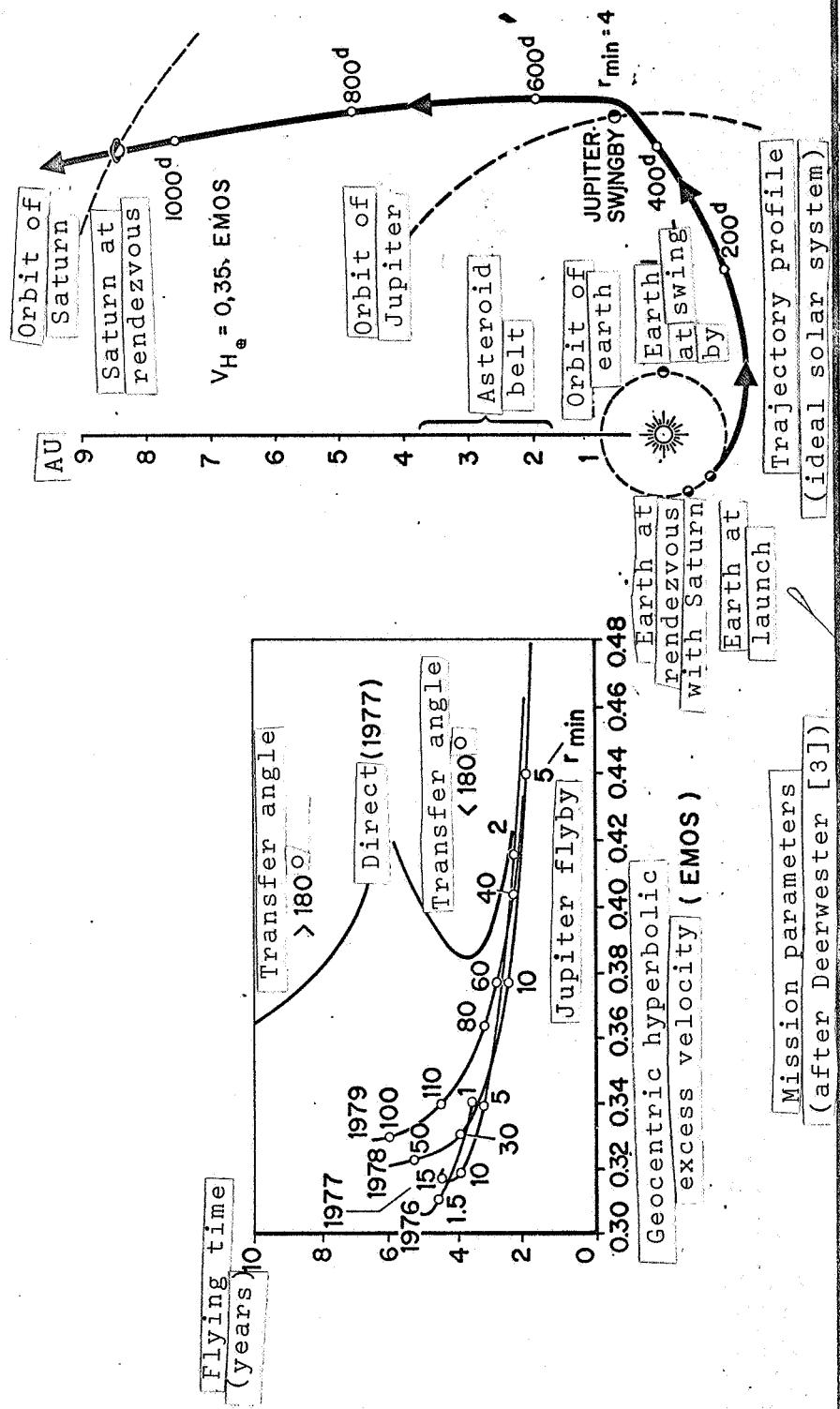
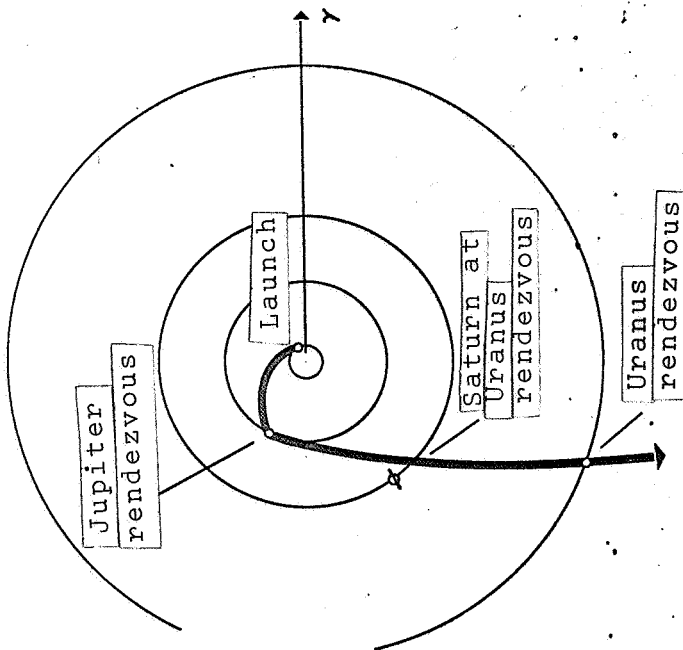
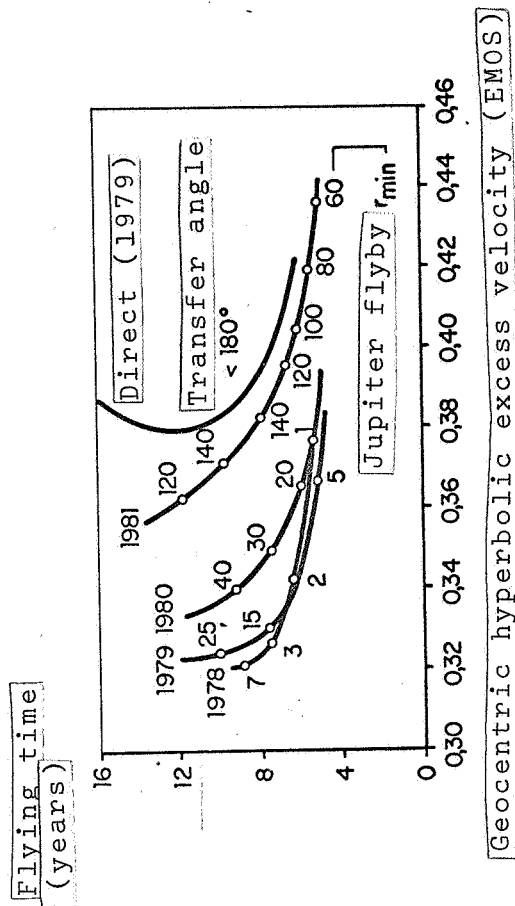


Fig. 7. Possible Applications of the Jupiter Swingby Mode.





Typical trajectory profile for 1978 launch (after Flandro [2])



Mission parameters (after Deerwester [3])

Fig. 9. Uranus Mission with Jupiter Swingby.

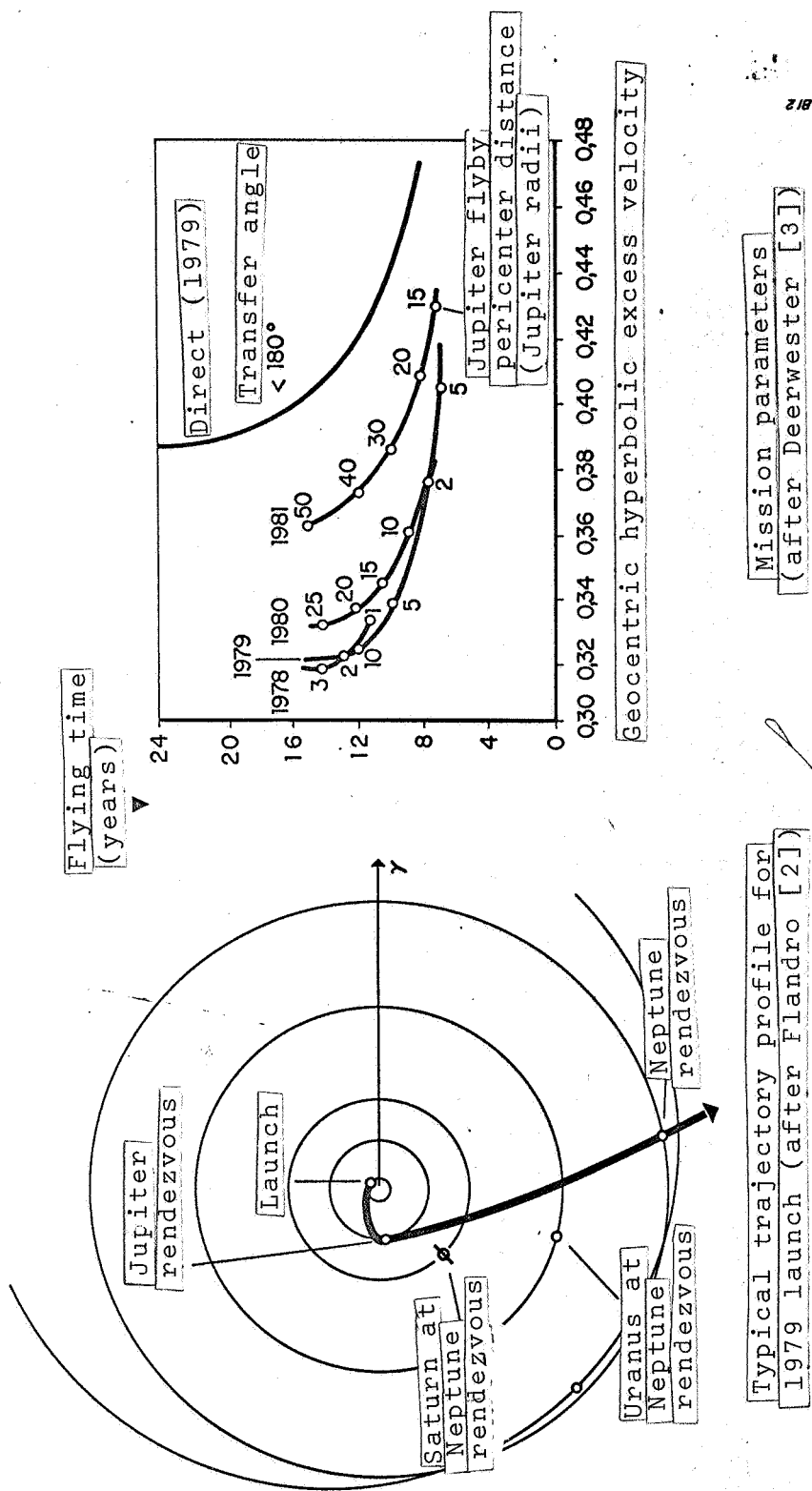


Fig. 10. Neptune Mission with Jupiter Swingby.

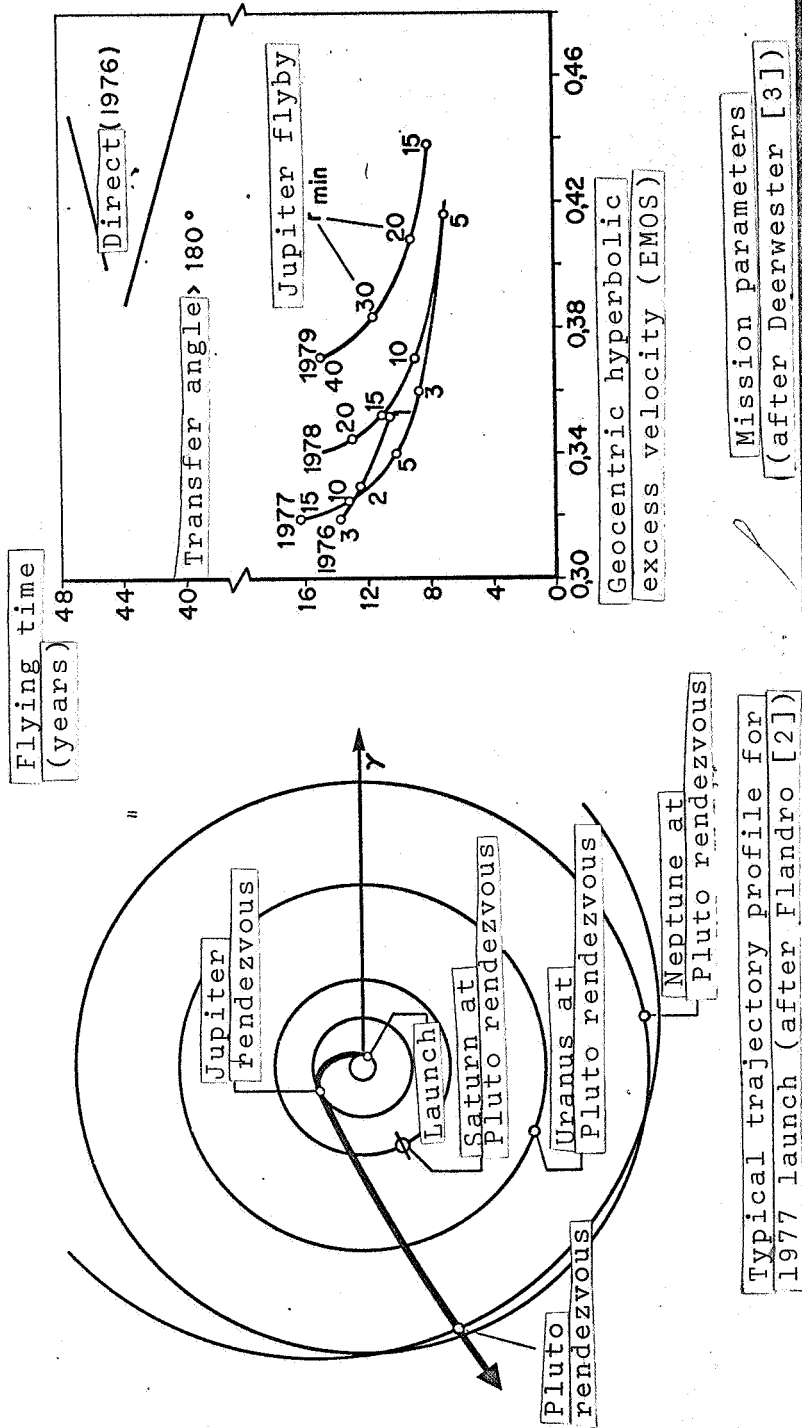
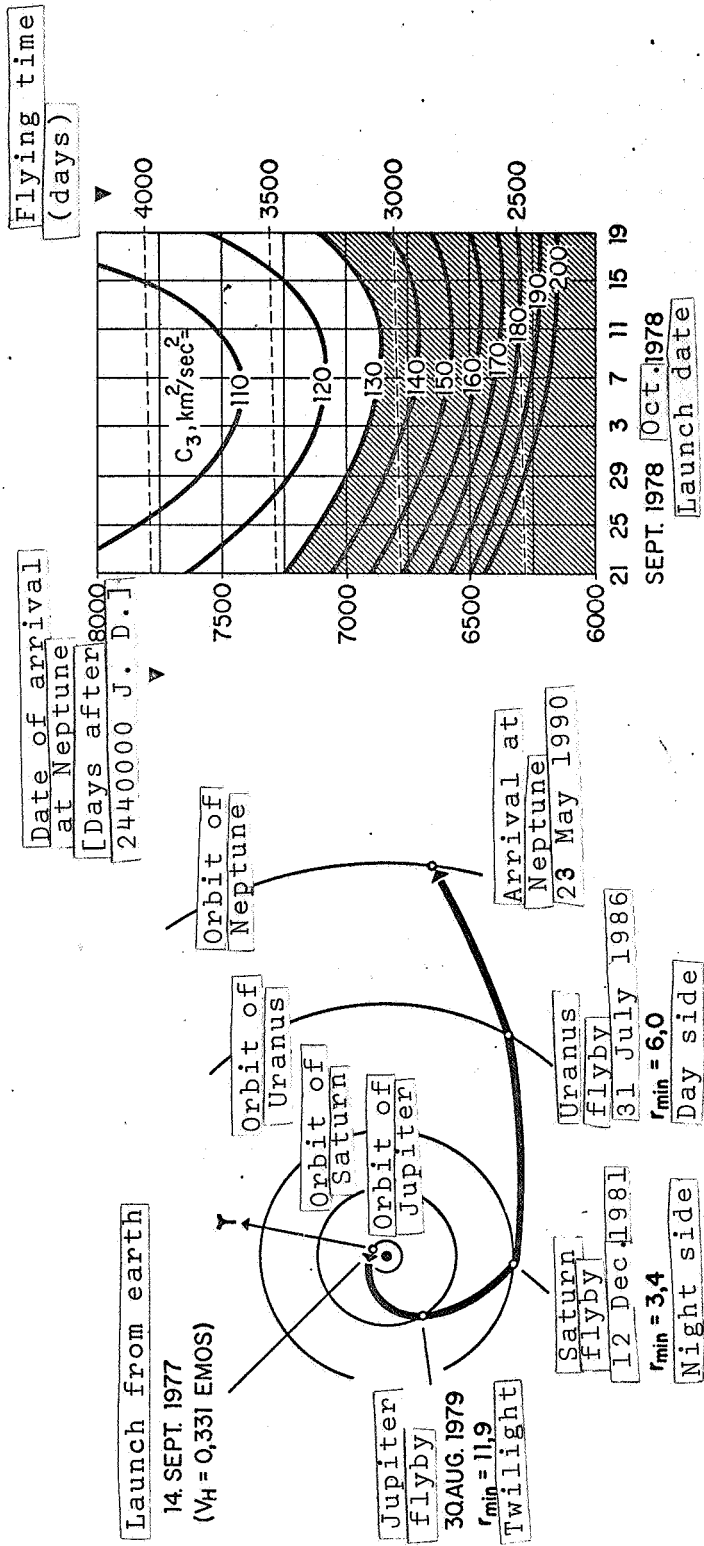


Fig. 11. Pluto Mission with Jupiter Swingby.



Arrival at Neptune as a function of launch energy and launch date (after Flandro [2])

Trajectory profile of the 1977 "Grand Tour" (after Deerwester [3])

Fig. 12. Triple Swingby Mission.

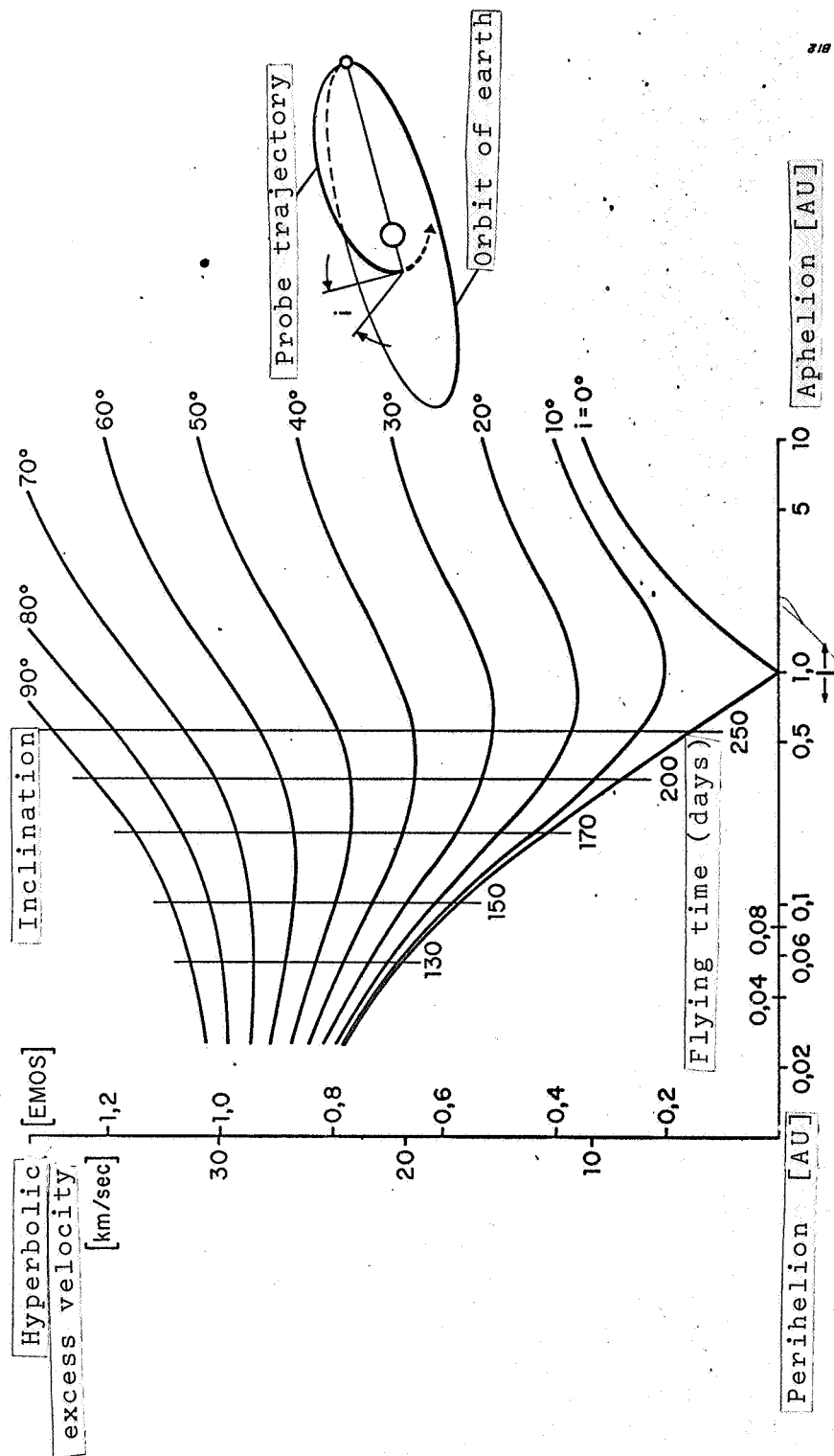


Fig. 13. Trajectory Parameters of a Direct Solar Mission.

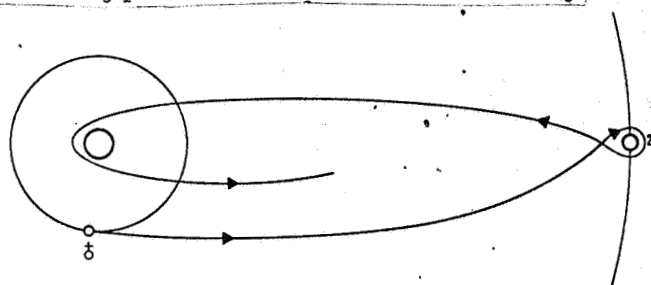
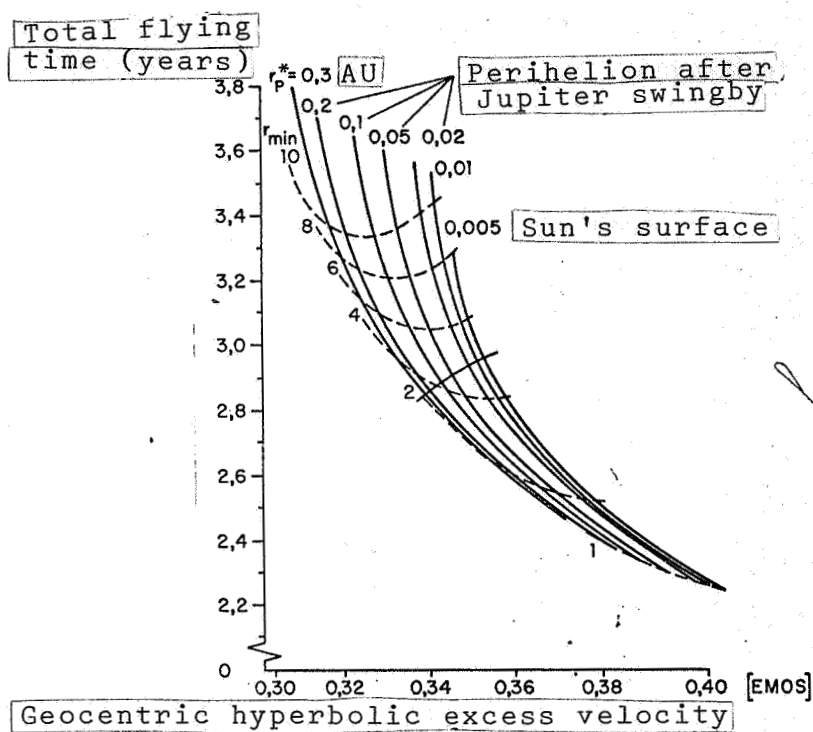


Fig. 14. Trajectoral Parameters of an Indirect Solar Mission with Jupiter Swingby (after Niehoff [1]).

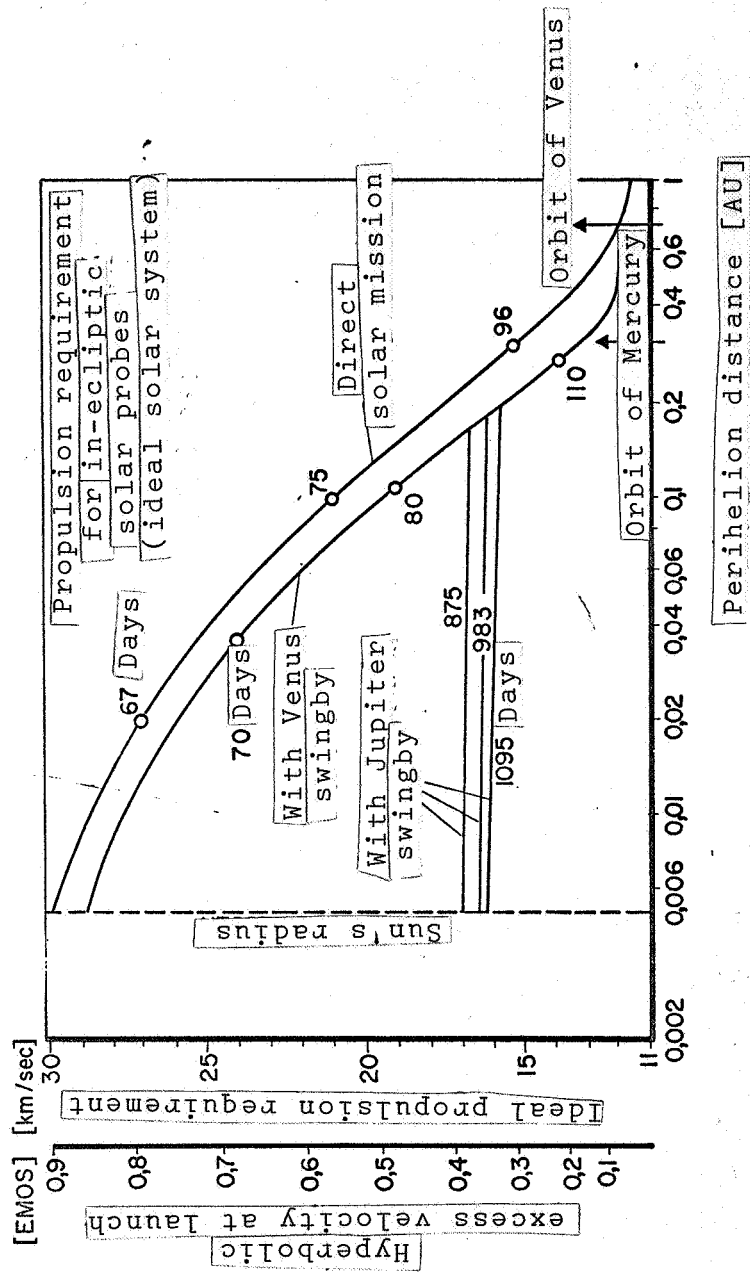


Fig. 15. Comparison of the Astrodynamic Possibilities for In-Ecliptic Solar Probes (after Niehoff [1]).

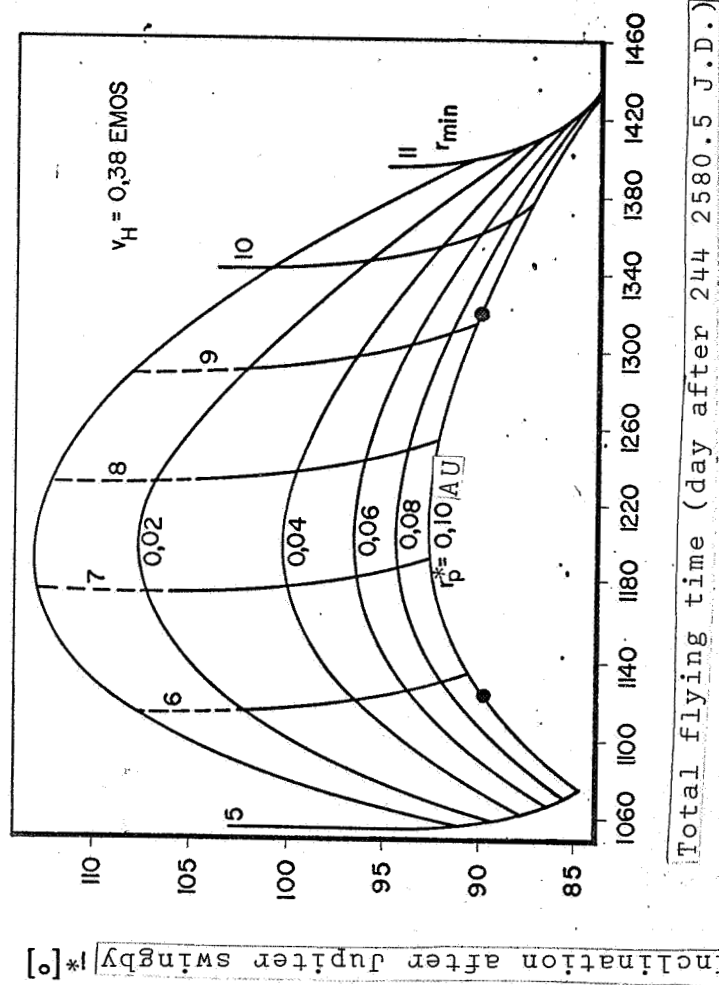


Fig. 17. Trajectorial Parameters of Out-of-Ecliptic Solar Probes after Jupiter Swingby (after Metzger [5]).

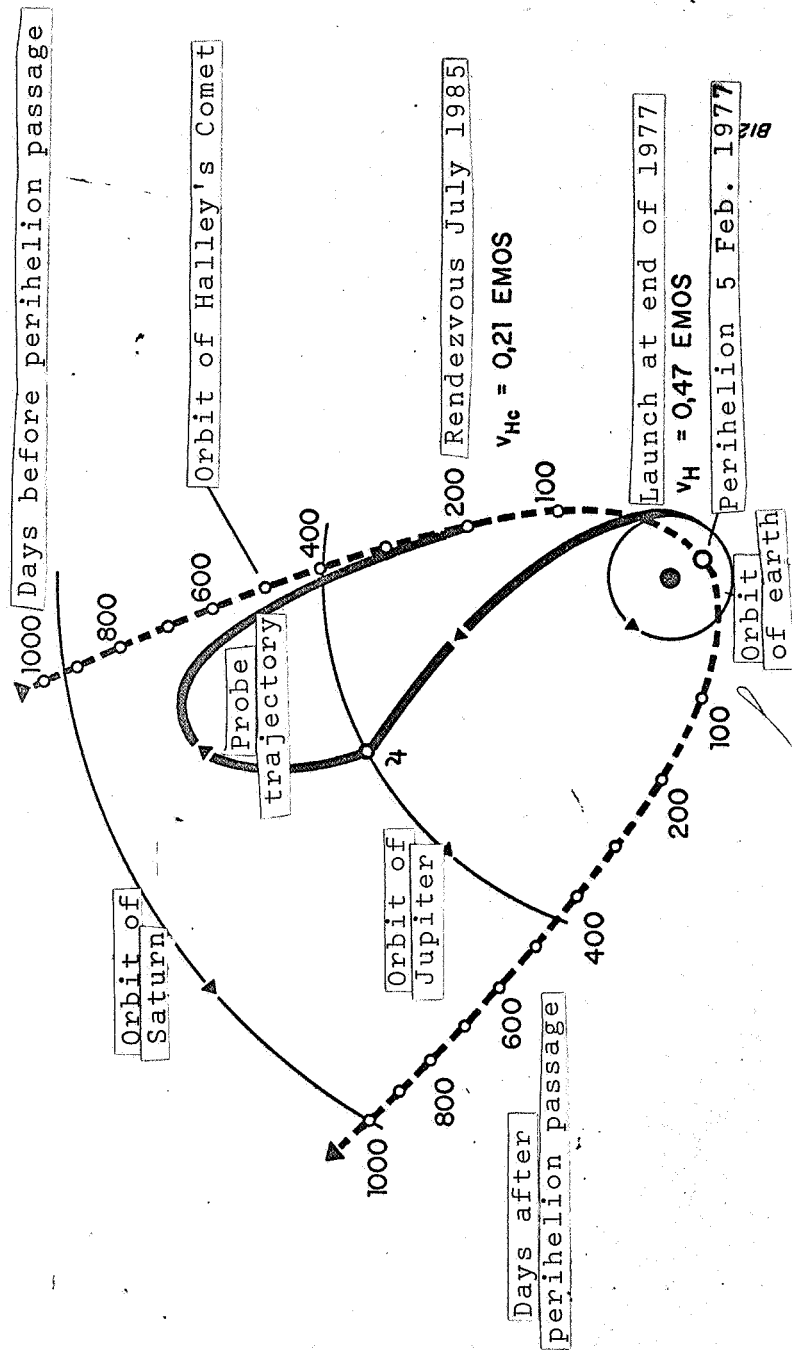


Fig. 18. Rendezvous of a Probe with Halley's Comet after Jupiter Swingby (after Michielsen [9]).

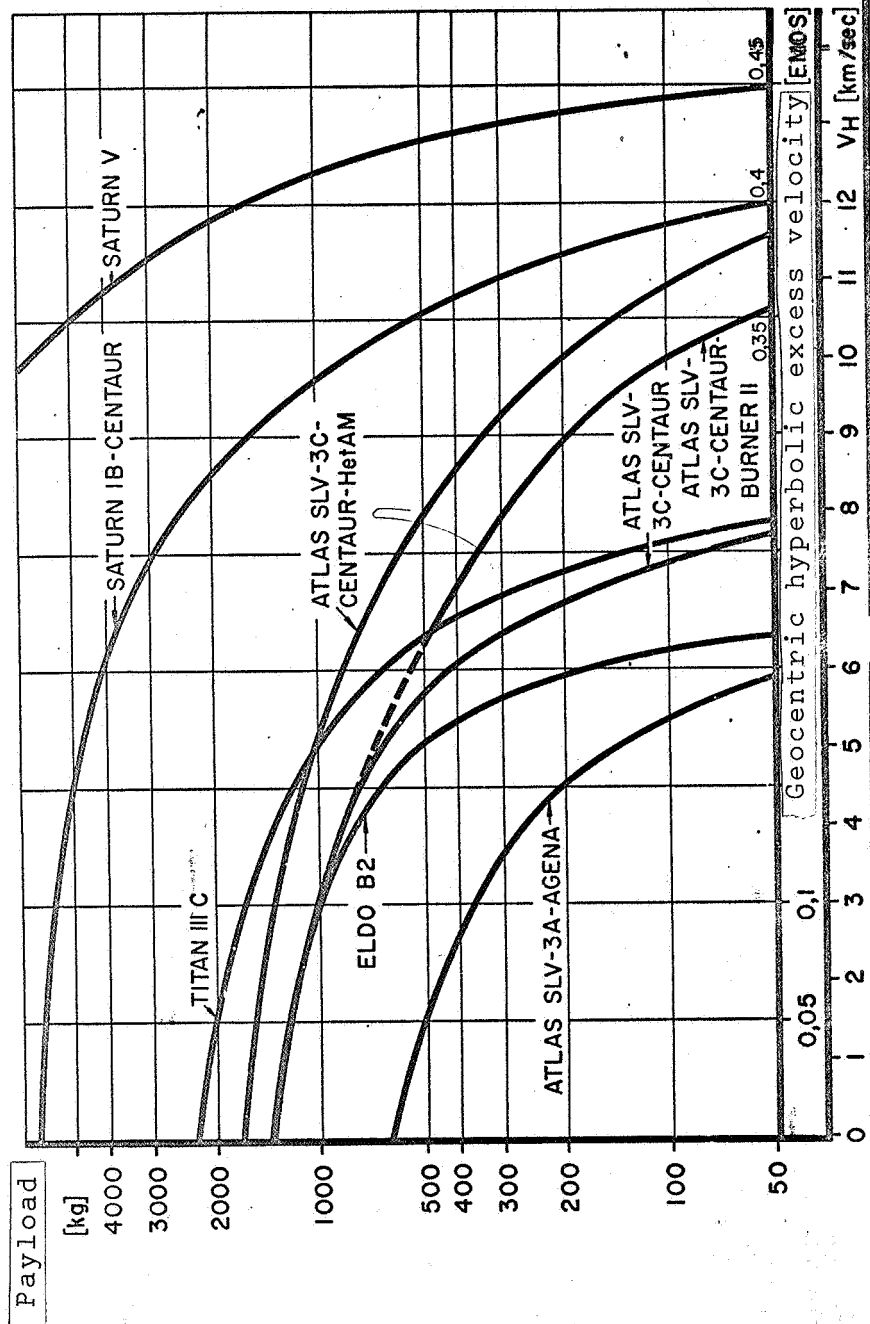


Fig. 19. Estimate of the Payloads of Launch Vehicles for Interplanetary Missions (after [14], [15]).